Natural Fibre Composites With 3D Woven Reinforcement for New Application Areas

Soden, J., & Stewart, G. (2010). Natural Fibre Composites With 3D Woven Reinforcement for New Application Areas. *Journal of Biobased Materials and Bioenergy*, *4*(2), 139-147. https://doi.org/10.1166/jbmb.2010.1078

Published in:
Journal of Biobased Materials and Bioenergy

Publication Status:
Published (in print/issue): 01/06/2010

DOI:
10.1166/jbmb.2010.1078

Document Version
Publisher's PDF, also known as Version of record

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Received: 3 January 2010. Revised/Accepted: 11 February 2010.

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Journal of Biobased Materials and Bioenergy
Vol. 4, 139–147, 2010

Natural Fibre Composites with 3D Woven Reinforcement for New Application Areas

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The cross-discipline research embodied in this paper has been generated from a technical textile design perspective, where the author, as an established technical weave designer, has developed 3D woven natural fibre preforms for composite production and subsequent testing. This research is a comparative study between commercially available 2D bi-axial woven plied composite laminate and 3D reinforced woven multiple layer composites using both flax and naturally derived viscose yarns for natural fibre composite applications. The objective is to determine the initial properties of two natural fibre 3D woven composites with relatively low fibre volume fraction and assess their performance against a standard natural fibre 2D woven fabric lay-up arrangement. In order to achieve this, the textile design and production cycle must be considered. The paper focuses on the design and assemblage of 3D woven textile preforms, discussing the complex design parameters associated with obtaining desired loom state fibre volume fractions within the 3D material. It also highlights the weave production issues that impact on the quality and integrity of 3D woven fabric architectures for flat and tailored reinforcements. Treatment experiments with 4% NaOH on flax yarns were attempted to establish if the woven fabrics would benefit from post-production treatment prior to resin processing to improve interfacial bonds between fibres and matrix. Once woven, it details the Vacuum Assisted Resin Transfer Moulding (VARTM) processing method using epoxy resin and presents initial results from mechanical test programs assessing flexural strength and damage resistance. By selecting a 2D 2/2 woven twill laminate and angle interlock (AI) 3D architecture as baseline control samples, an early assessment will establish the benefits and challenges these materials face, and their future potential. Findings from the research indicated that Alkali treatment of flax yarns was found to decrease the virgin and impregnated yarn tensile properties as well as the flexural strength and stiffness properties of the 3D woven angle interlock composites. 2D twill flax composites achieve a higher fibre volume fraction which, in turn, leads to superior flexural properties with respect to 3D AI composites. 2D 2/2 twill viscose rayon composites flexural strength and modulus were found to be superior to 3D angle interlock structures but inferior in damage resistance. The damage characteristics from impact resistance tests show differences in damage area, impact depths and the dispersal of subsidiary cracking. Test specimens demonstrate that 3D woven viscose rayon composites displayed mostly localized damage around the location and did not allow the damage to radiate out substantially which is in contrast to the delamination damage observed in the 2D material.

Keywords: Woven, Preform, Natural Fibre Composites, Vacuum Assisted Resin Transfer Moulding (VARTM).

1. NON-WOVEN NATURAL FIBRE PREFORMS

With the implementation of EU directives[1] on waste and end of life disposal strategies, there has been a surge of activity driven by the European Automotive Industry to introduce Natural Fibre Reinforced Composites (NFRC) as a substitute to glass-fibre reinforced plastic (GRP), where appropriate.

With sustainable, lower environmental production impact and lightweight attributes, matched with low cost in comparison to glass fibres as driving factors[2,3] natural

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 1556-6560/2010/4/139/009 doi:10.1166/jbmb.2010.1078

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fibre nonwovens have desirable characteristics for use in acoustic insulation, interior trim and secondary non-critical vehicle parts such as parcel shelves and door inserts. Material data is continually being generated allowing greater usage and integration into further applications.

The expenses associated with raw materials and components, the material weight and the ability of the material to be processed using existing large scale industrial composite processing technology are also important factors to consider.[3] The restriction in increased uptake of NFRC's thus far, has been due to the natural variability and inconsistency of the materials, the limited mechanical performance of non-woven and plied lay-up preform assemblies, the lack of commercial availability and lack of proven performance of a naturally derived bioresin to form 100% recyclable composites, and cost.

Textile preforms for use in fibre reinforced composite applications utilize fibres and/or yarns to produce non-woven, filament wound, uni-and multi-directional, woven, knitted, braided, bonded, and stitched preform constructions. Within the natural fibre composite domain, non-wovens are the prevalent reinforcement method used and offer a cost effective, efficient production range of non-load bearing materials that often integrate waste from other textile processes and utilize indigenous natural fibres within their geographical locality.

Natural fibre preforms are primarily derived from cellulose-based matter in the form of agricultural waste from a variety of crops and grasses, low-grade decorticated bast fibre or refined shive.[4] They are manufactured using non-woven production techniques where short, chopped, random or mixed fibres are randomly or systematically laid-up in multiple thin layers via air, water or chute-feed mechanisms to produce fibrous mats in a range of areal densities. Sheet moulded compound (SMC) fibre panels are formed from flax, hemp, hybrid natural fibre combinations, sisal, coir, or polyesters,[5] where they are assembled and consolidated via an adhesive synthetic binder, bonded via hot-pressed prepreg sheets or compression moulded to form panel products. Interestingly, non-wovens can be further reinforced in an organised manner by surface machine stitching or needle-punching, the process whereby a needle plucks fibres from surface layers and pulls them through to deposit them in the through-thickness or Z-axis orientation. This provides controlled and premeditated fibre placement, a behaviour more closely associated with woven fabric design. Thermal fusing fibres[6] can provide an additional thermal bond, thus improving the mat's structural properties.

Problems reported with these mats includes the 'non-homogeneity' of the fibres and presence of contaminants such as shive,[6] lines of weakness as a result of the impaling action of the needle, and poor conformability of higher density mats to small radius curvature for near-net-shaped components. The lack of continuous fibre integrity within 2D plied lay-up assemblies is a significant factor which inhibits their development and selection for higher specification structural parts.[7]

2. JUSTIFICATION FOR 3D WOVEN PREFORMS

Goutianos[8] stated that in order to enable the use of natural fibre composites in high-quality engineering applications, the development of unidirectional tapes, and non-crimp and woven textiles was required. The introduction of a 3D woven structure enables premeditated design and organization of the 'weave architecture', or arrangement of yarns within the layers of the fabric. Exact tailoring of yarn reinforcement provides specific areal densities within each layer of the reinforcement and allocations of yarn roles and functions determine the placement of that reinforcement to provide a material with yarns positioned in the Warp (X-axis), Weft (Y-axis) and Through-the-thickness (Z-Axis) orientations. A customized fabric can be designed to respond to the demands of its intended application. However, to manufacture bespoke tailored materials, higher specification, more costly woven technologies such as multi-shaft Dobby or advanced Jacquard technology is required, which requires investment up-front in order to establish their mechanical and economic credentials before being streamlined for use.

The potential of natural fibre 3D woven composites for structural applications are currently being developed and assessed, mainly at prototype and small-scale production levels by the author.[9] By investigating the main technical challenges, prototype examples have emerged, which include composite specimens for the generation of mechanical property data, near-net shaped prototypes for transport and performance automotive[10] (Fig. 1), thick reinforcement damage resistant panels, and prototypes with multi-functionality targeted at new eco-building concepts and infrastructural uses.

This research is still at the pioneering stage; technical performance needs to be rigorously demonstrated for assigner and user acceptance, the cost value chain needs to be clarified and the advantages effectively communicated.[11] By using a well established, angle interlock 3D weave architecture,[12] base-line data can be compared with other fibre types woven in this structure and understood by a greater scientific audience who have previously used this structure in their research.

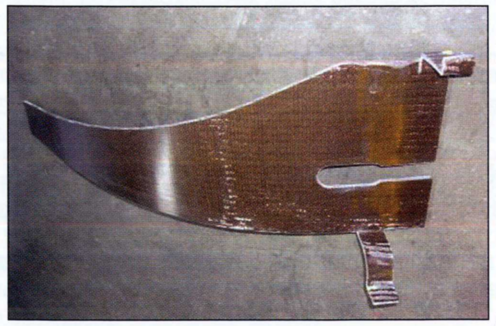

Fig. 1. 3D Woven flax bargeboard component for worlds first sustainable racing car.

3. THE WEAVE DESIGN AND PRODUCTION CYCLE YARN DESIGN

In order to achieve continuous fibre integrity, a construction process such as weaving is required so continuous lengths of yarn (or tows) can be assembled into an organized structure. The yarn is the key component in this system and although the fabric architecture has significant influence on the overall properties of the preform, it is ultimately reliant on the core attributes of the fibre used in the core yarn.

The grade of raw fibre material from the field varies between batch yield, country of origin and species. The quality and level of fibre preparation, cleaning, refining, and combing directly relates to the price and quality of the final yarn produced. Splicing, ply-design, twist frequency and resultant conformability/handle characteristics of the actual yarn need to be designed with a specific production machine in mind. High twist in a yarn can reduce its reinforcing efficiency; however it is usually necessary to withstand the weaving process. Other factors that need to be considered are yarn properties in longitudinal and transverse directions, friction, and static, developing hybrid yarn mixes, the yarns absorbency properties and compatibility with the resin matrix.

Cost of quality flax yarn (400 Tex) ranges from €2–10/kg. Cheaper flax yarns exhibit poor fibre quality, insufficient strength and are subject to extensive fibrillation damage and fibre degradation during fabric manufacture. Choice is therefore constrained to more refined plied yarns or pre-finished, high specification yarns.

Natural fibres are subject to treatment preparation, shrinkage, degradation and non-uniformity in comparison to glass or carbon fibres. It is expected that developing and optimizing the sizing agent and compatible chemical treatments for enhanced adherence between yarn and resin matrix needs to be expedited by yarn producers in order to supply the optimum yarn for woven materials.

High tenacity viscose rayon yarns, containing fibres that are naturally-derived from wood pulp, yet synthetically produced are also included in this study. These yarns have been synthetically modified by the manufacturer to produce consistent properties. The fibre does not require treatment and achieves good thermal and adhesion compatibility with the resin matrix. Other attributes include quality certified consistent production, good fibre properties, small batch supply and reduced cost compared to flax. It therefore presents itself as a potential alternative to flax.

Table I. Results of flax yarns untreated/treated.

	Virgin		Impregnated (Epoxy)	
Flax yarns	Untreated	Treated	Untreated	Treated
	—	4% NaOH	—	4% NaOH
Tensile strength (MPa)	82.38	20.93	71.34	62.55
Tensile modulus (GPa)	5.0	1.2	5.4	5.4

4. YARN TREATMENT

The pretreatment of natural fibres is recommended to improve fibre/matrix interfacial adhesion[13,14] Alkaline, saline or enzyme treatments can be used. However, the benefits of fibre treatment come at a price in terms of the decrease in mechanical properties. Comparisons were made on the inherent untreated properties of flax yarns treated with 4% sodium hydroxide (NaOH). Flax yarns (400 tex), both treated and untreated were prepared with a 150 mm gauge length, tabbed with 3 ply 25 mm × 35 mm cardboard tabs and subjected to tensile testing according to BS 10618. The treatment with sodium hydroxide had a significant negative effect on the tensile properties of the flax yarns. Drops of 73% and 76% in strength and modulus were evident in the virgin yarns. Epoxy Impregnated yarns sustained an 11% drop in strength but no change in the modulus (see Table I).

To test this hypothesis further, both an alkali-treated and untreated composite preform was included in the flexural test program. This is known to lead to improved composite properties as the alkaline solution induces removal of pectin and lignin in the natural fibre, increasing aspect ratio, which can be advantageous to composite performance.

5. 2D WOVEN LAMINATES

Single layer woven plies that rely on the reinforcement-matrix interfacial strength are common in composite reinforcements. Multiple plies of fabric form stacked laminates to obtain the desired composite thickness. Fabric manufacturers in Europe[15] have responded to the resurgence in demand for 2D woven flax by producing heavier fabric densities in finished cloth (up to 600 g/m^2, price approx. €20 per sq. metre for small quantities) and also a flax prepreg material for use in composites.

The following laminate baseline control samples were prepared for the comparative study: A flax bi-axial woven laminate using 5 plies of commercially available flax fabric, 550 g/m^2 in a 2/2 twill weave. A similar 2D viscose woven laminate was fabricated using 4 plies of 2/2 twill construction. This material was not commercially available, so was fabricated in-house as a separate layer stack. Attempts were made to achieve similar construction densities between the two fabric types, however due to varying machine density settings this was not possible.

6. 3D WOVEN YARN ROLES WITHIN ARCHITECTURES

3D woven materials are complex constructions. They utilize multishaft Industrial Dobby and Jacquard weaving technology to assemble yarns in thick, multiple layer stacks with designated warp yarn paths interlinking these layers together in the warp (0°), and through-the-thickness orientation.[16] Weft yarns (90°) are inserted via shuttle, rapier or on specialist looms, via multi-insertion needle systems. Yarn interlacement and levels of inherent crimp are present in these architectures, whose primary function is to reinforce.

Warp yarns are designated one, or a combination of the following roles:

1. In plane interlacement where yarns interlace within the layer of origin.
2. Low-crimp (or non-crimp) warp stuffer: to reinforce in the warp orientation (Fig. 2).
3. Through-the-thickness interlink/interlocker: Warp yarns that migrate through a proportion of, or the total fabric thickness in a variety of perpendicular or angled stitches. These may follow traditional twill or satin interlacement sequences (Fig. 3).
4. Selvedge yarns: To either stabilise inserted weft yarns or act as sacrificial yarn that will be assigned to waste after production.
5. Supplementary warp yarns: yarns that float until programmed to weave intermittently and provide specific reinforcement in key areas.
6. Tailored, localized or through-intersection support: Yarns that are primarily arranged to interlace in a specific locality or over a designated area for a specific function (e.g., intelligent fibres, thermoforming), or yarns that migrate through the intersection of a shaped structure to provide continual fibrous reinforcement. (e.g., in structural beams or hollow-sectioned reinforcement).
7. Weft fill paths can operate in-plane or also interlace out-of plane across the fabric width.

3D woven architectures have enhanced near-net shaping capabilities depending on the capacity and configuration of the Jacquard head or Dobby control mechanism, and can successfully designate individual and/or grouped

Fig. 2. Low crimp warp stuffers with viscose through-the-thickness binder.

Fig. 3. Twill multiple layer reinforcement.

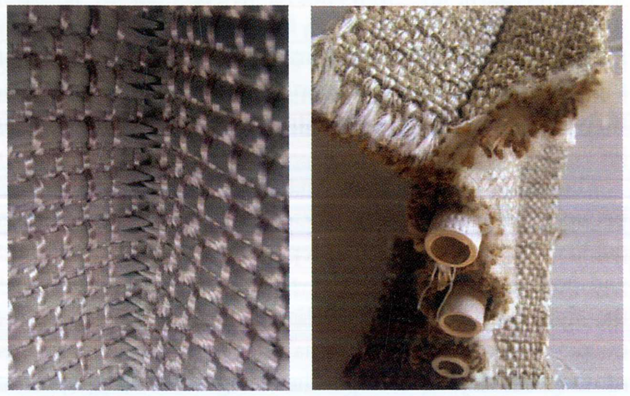

Fig. 4. Through-intersection reinforcement in X-profile (left) and I-beam (right).

yarn paths into specific key stress areas of the material for bespoke tailoring and additional reinforcement, such as around mechanical joints, edges and particularly at junctions and interfaces[17] (Fig. 4). Additional reinforcement is also useful around window shapes. Unique warp paths and hybrid combinations of structure, yarn types and yarn counts are possible within a single preform, but are costly and challenging to produce.

7. FACTORS AFFECTING PREFORM AREAL DENSITY IN 3D WOVENS

Obtaining desired loom state areal densities is a complex operation as ideally, the ultimate objective is to concentrate efforts to design the 3D reinforcement with high areal density in loom state condition so minimal pressure is required during resin consolidation to achieve the desired composite fibre volume fraction. This is to prevent unpredictable distortion and misalignment of yarn paths and localized variations in architecture due to excessive compaction within the tool. VARTM is the natural processing route for these materials due to low consolidation pressures and clean efficient transfer of resin to the integrated reinforcement. Other production factors that affect the achievement of high areal density include:

1. Machine parameters: The number of Dobby loom shafts or size and configuration of the Jacquard head determines

the maximum yarn capacity that can be accommodated per cm and configured for use within the multiple layer architecture.
2. Warp density and spacing must be planned to ensure straight alignment, minimal abrasion and ability to form a clean shed for weft insertion.
3. Yarn choice: The yarn characteristics, texture, handle, count and conformability influence the density it can be fabricated into reinforcement. For instance, a hairy, bulky flax yarn with lively twist and high friction resistance will usually not achieve as high an areal density as flat, smooth and conformable yarns.
4. Automatic take-off or cloth advance systems: The ability to slow or intermittently stop the auto-advance mechanism assists with the formation and build-up of well aligned weft pick columns, enabling good packing density for weft yarns and ultimately higher areal densities.
5. Weave architecture: The range of yarn roles, their configuration within the architecture and the weave structure assigned has a significant impact on the construction integrity and achievable areal density. The weft packing density also influences the non-perpendicular slant of through-the-thickness binder stitches. The intention is to minimise the amount the structure will deform in the tool.
6. Relationship with Resin Processing: Looser weave architectures with lower areal densities encourage yarn misalignment and slippage, thus compromising structural integrity. However, by having some natural spaces within the construction, resin is able to find a natural flow channel through the preform without forcing yarn paths to buckle under the pressure of resin injection. Very dense arrangements (55%+vf) can present substantial resistance to resin flow, resulting in areas with poor wet-out.

8. 3D WOVEN PREFORMS USED FOR THIS STUDY

For this study, flax (1700 g/m^2) and viscose rayon (1500 g/m^2) angle interlock preforms consisting of 4 layers have been selected. Warp yarns contribute both to the X-Axis and the Z-Axis reinforcement by systematically migrating through the total thickness at an angle of approx 45° as illustrated in Figures 5 and 6. This forms a structure with equal yarn path lengths between layers and provides

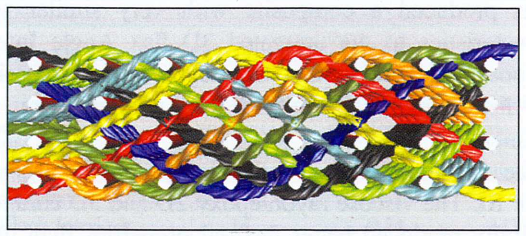

Fig. 5. Angle interlock yarn paths.

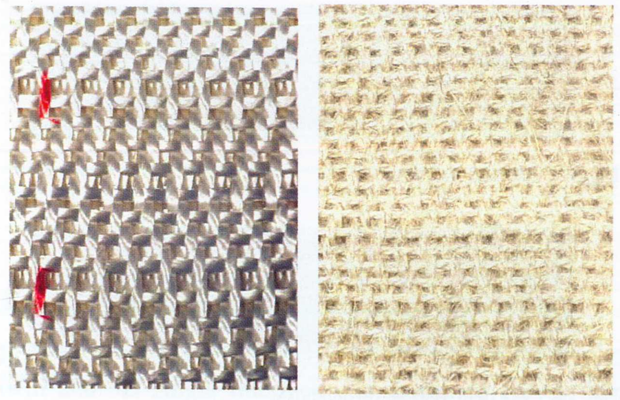

Fig. 6. Viscose preform (left) and flax preform (right).

Fig. 7. 3D angle interlock flax/epoxy.

Fig. 8. 3D angle interlock viscose rayon/epoxy.

a uniform preform surface for consolidation in the mould tool.

Spun flax yarns are bulky and textured in nature which helps retain their cross-sectional shape and resist deformation in the preform. Viscose rayon yarns are slippy in nature and are prone to distortion and flattening to an elliptical shape within the preform. This is reflected in the varying preform thickness between the fabric types and is pronounced in the cross-sectional micrographs in Figures 7 and 8.

9. PREFORM ANALYSIS AND DETERMINATION OF FIBRE VOLUME FRACTION

Polished micro-sections were used to analyse the weave architecture of the textile composites along the warp orientation as shown in Figures 7 and 8. Both 3D woven preforms experienced 15% compression during consolidation. The flax/epoxy composite yarns migrate through the thickness at 45° approx. (Fig. 7) displaying good alignment free from distortion, with the angled yarn paths of the interlock architecture clearly intact.

This contrasts to the 3D viscose rayon/epoxy architecture (Fig. 8) in which yarn slippage, high levels of crimp and deformation is evident in the migrating yarn paths,

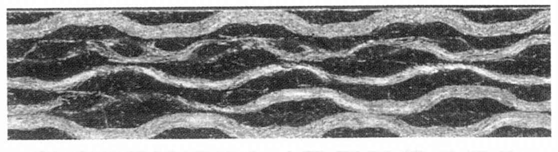

Fig. 9. 2D twill flax/epoxy.

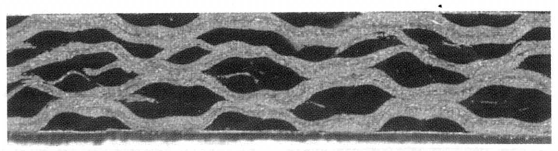

Fig. 10. 2D twill viscose rayon/epoxy.

Table II. Characteristics of composites.

Specimen	Thickness (mm)	Density (kg/m^3)	Composite V_f (%)
2D twill 2/2 viscose/epoxy	2.40	1461	61
3D Angle interlock viscose/epoxy	2.08	1560	40
2D twill 2/2 flax/epoxy	4.01	1131	45
3D Angle interlock flax/ epoxy untreated	4.74	1264	19
3D Angle interlock flax/ epoxy treated	4.43	1211	20

along with a reduced through-the-thickness yarn inclination angle approximating 30°.

Micro sections of the 2D 2/2 twill viscose rayon and flax composites (Figs. 9 and 10) show regular interlacement with the viscose 2D twill, showing a high density structure but with higher levels of crimp in the yarns.

Subsequently the V_f obtained for the 2D viscose composite (Table II) was 61%, higher than the 40% measured for the 3D viscose rayon Angle Interlock (AI), a consequence of warp end density and twill weave which enables high pick densities.

Fibre volume fraction tests were carried using the density buoyancy technique on a Mettler Toledo XS64 at 17.4 °C. A few drops of a wetting agent were added to distilled water and the density of the materials calculated via displacement according to ASTM D 792-00. At least three composite specimens were tested per structure and based on visual evidence from polished cross-sections, no voids were present in all composite samples.

10. RESIN PROCESSING

A two-part epoxy resin system; Araldite LY-564 epoxide and an Aradur HY 2954 curing agent was used as the baseline resin matrix. Both epoxide and amine curing agent were supplied by Saint Gobain Vetrotex. A mixing ratio of 100:35 by weight of epoxy to curing agent was used as recommended by the manufacturer to create a stoichiometrically balanced epoxy resin. The epoxy was out gassed for 60 mins at 30 °C prior to injection.

Vacuum Assisted Resin Transfer Moulding (VARTM) was used to manufacture the composites. All preforms measured 350 mm × 350 mm. A 4% sodium hydroxide alkali treatment, as per yarn treatment, was undertaken on one angle interlock flax preform prior to consolidation to establish its effect on flexural properties. The dry preforms were placed in the mould, flexible tooling allowed 100 kPa pressure to compact the preform and the resin was injected into the mould under 75 kPa at 75 °C for the epoxy composites. Wet out of the preforms occurred after 7.5 minutes... After wet-out the viscose rayon/epoxy composite was ramped to 100 °C at 0.64 °C/min and held isothermal for 60 minutes. Composites were subject to a post cure of 8 hrs at 145 °C. Wet out of the preforms occurred after approximately 7.5 minutes. Moulded thicknesses of 2.4 and 4.6 mm were achieved for the viscose rayon and flax composites respectively.

11. MECHANICAL TESTING

Flexural tests were carried out according to ISO14125 using a three point bend configuration with a span to thickness ratio of 25/1 and 10 mm diameter load/support rollers using a Zwick Z100 universal testing machine. All samples were 10 mm in width. Five samples were tested per composite at a test rate of 10 mm/min and all samples failed within 30–180 seconds.

An Instron Dynatup 9250HV drop weight impacter is used to carry out low velocity impact tests on the 2D and 3D woven fibre reinforced composites. All plates had equal width and length (100 × 150 mm). The plates were clamped at each corner and the impact applied to the centre of the plate. An impact mass of 6.5 kg and a 19 mm diameter hardened steel hemispherical striker tip was used to impact 5 samples of each plate. The impacts were exerted at different energies to enable an energy/thickness ratio of 6.7 J/mm as per ASTM D7136/D7136M-05. The low velocity impacts produced visible damage on the outer surfaces of the composites such as resin crack, fibre crack, fibre/resin debonding as well as partial collapse. These damage configurations are observed visually, being characterised by damage area, shape and indentation depth.

12. RESULTS

The 3D flax Angle Interlock composites with alkali treated yarns produced a composite with very similar spatial characteristics to the untreated 3D flax Angle Interlock composite, indicating that the degree of compressibility and distortion of the structure was unaffected by alkali treatment.

The flexural results of the composites are given in Table III. The viscose rayon/epoxy 2D and 3D composites generally produced better flexural properties than the 2D and 3D flax composites. Comparing the performance of the

Table III. Flexural results of composites along the warp direction.

Samples	Average flexural strength (MPa)	s.d. (MPa)	s.d. (%)	Average flexural modulus (GPa)	s.d. (GPa)	s.d. (%)
2D twill 2/2 viscose/epoxy	237.61	5.10	2.15	10.65	0.03	0.28
2D twill 2/2 flax/epoxy	141.73	4.08	2.87	10.86	0.25	2.30
3D AI viscose/epoxy	168.55	10.16	6.02	6.67	0.51	7.64
3D AI flax/epoxy untreated	68.80	6.13	8.90	4.60	0.28	6.08
3D AI flax/epoxy treated	66.54	6.64	9.97	4.03	0.16	3.97

2D viscose rayon against 2D flax composites, the strength of the 2D viscose composites is substantially higher however the modulus of both are in the comparable range. The 2D viscose composite out-performed the 3D Angle Interlock viscose composite aided by its substantially higher V_f (40% vs. 61%) The 2D flax composites achieved superior performance compared with the 3D treated and untreated 3D Angle Interlock flax composites. This is attributed to the variation in V_f of 45% compared to the 19–20% V_f achieved for the 3D Angle Interlock composites.

Overall the results compare favourably with other work conducted in flax soy resin composites by Huang[18] where unidirectional yarn composites possessing 48% V_f obtained values of 82–117 MPa and 4.7–7.6 GPa in flexural stress and flexural modulus respectively. Huang also reports that flax fabric reinforced composites with 4 layers of laminate ply and possessing a 43% composite V_f obtained flexural stress values of 20.9–25.2 MPa in the warp orientation and 0.7–1.29 GPa in flexural modulus.

Higher V_f of 27–31% was achieved by Liu and Hughes[19] for 2D epoxy/flax laminates. They found that a high V_f was a key driver in delivering improved fracture toughness and also concluded that with superior yarn and textile design, a better overall balance of stiffness, strength and fracture toughness is achievable. Another example in this area includes the work done by Williams and Wool[20] who found values of 64 MPa and 4.2 GPa for 34% V_f non woven flax/soy-oil based composites. Wool[4] states that in a hemp reinforced composite properties possessing a 24% V_f, a tensile modulus of 4 GPa can be achieved. A glass fibre laminated composite using bio-based resin and possessing a 45% V_f was found to achieve flexural strength of 260 MPa and flexural modulus of 11.3 GPa. Results from Oksman[21] and Heijenrath and Peijs[22] state flax composite mats with a 47% V_f can obtain similar stiffness to glass fibres using epoxy and polypropylene matrix but with reduced strength.

13. DAMAGE RESISTANCE

Low velocity impact tests were carried out on the 2D 2/2 twill and 3D Angle Interlock composites to access their damage resistance properties and investigate the ability of the through the thickness reinforcement as a means to increase damage tolerance. Table IV shows the damage created by the impact of the 6.5 kg striker tip. Due to the slight difference in plate thickness the nominal impact energies and therefore drop heights are slightly different. The mean damage area is reduced by approx. 19% in the 3D Angle Interlock composites compared with the 2D 2/2 twill composites. Representative images of the damage areas are shown in Figures 11 and 12.

The damage patterns are visibly different. The 2D twill composite displays a large rectangular damage area around the impact location (Fig. 11 right) with regular resin cracking observed in a 2:1 ratio in the warp/weft directions, indicating the damage develops to a larger extent along the warp yarns which is common in textile composites.[23] In contrast, the 3D Angle Interlock composite displays very localised damage in a 10 mm radius surrounding the impact location with a damage pattern of faint resin cracking (warp direction only) radiating out from the corners of the damaged area in an X-shape (Fig. 12 right). Crack-free triangular shaped areas between the corners can also be observed in Figure 12. The mean maximum damage diameter and mean dent depth are lower in the 2D twill composite. These results show the 3D Angle Interlock composite has developed a higher degree of localised damage at the impact event but the level of damage is shown to decrease significantly as distance increases from the location, due to the binding effect of the though the thickness reinforcement. In contrast, uniform damage is observed all along and up to the limits of the visible damage in the 2D twill composite.

The larger area of more consistent damage in the 2D twill composite would usually be representative of a lower

Table IV. Damage in viscose rayon composites.

Composite	Nominal impact energy (J)	Drop height (m)	Mean damage area (mm^2)	s.d. (mm)	s.d. (%)	Mean maximum damage diameter (mm)	Mean dent depth (mm)	s.d. (mm)	s.d. (%)
2D twill 2/2 viscose rayon/epoxy	17	0.30	2997.01	197.34	6.67	81.00	1.18	0.72	60.95
3D AI'lock Interlock viscose rayon/epoxy	14	0.24	2431.25	517.61	21.28	101.10	3.62	1.14	31.60

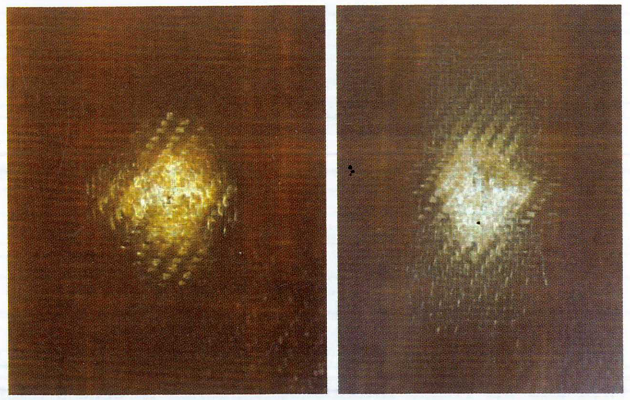

Fig. 11. Damage area in 2D twill laminate (left) top surface, (right) bottom surface.

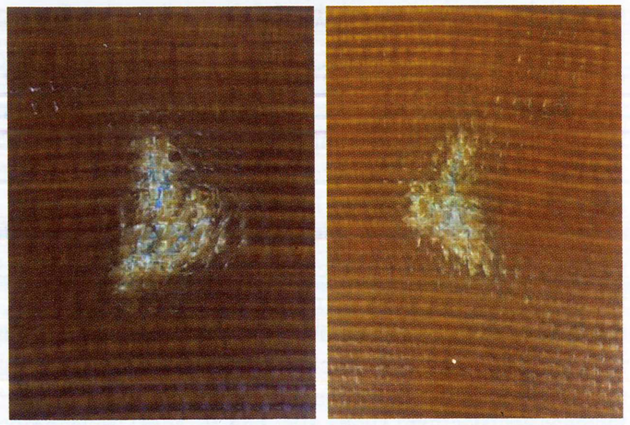

Fig. 12. Damage area in 3D angle interlock composite (left) top surface, (right) bottom surface.

residual performance. This will be examined in the next phase of this research where Compression After Impact (CAI) testing will be used to assess the residual performance of these composites.

14. DISCUSSION

These results clearly indicate the necessity for individually tailoring a 3D weave architecture for specific applications. The warp sett density of yarns allocated into each layer of 3D weave architecture would benefit from an increase to enable volume fractions within layers, and in turn the whole component, to improve. Machine capacities present restrictions in this regard. Through-the-thickness yarn stitches disrupt the uniformity of the structure and prevent maximum packing density from being achieved. Providing finer density through-thickness yarns in a less invasive linking structure should alleviate these issues. Assigning straighter stuffer yarn roles to a higher percentage of warp ends and interspersing these with through-thickness yarns should enhance properties.

Evidently, the handle and behaviour of the yarn type chosen and the distortion caused during the weave process are largely responsible for the deformation of yarns within the composite and ultimately the establishment of the final composite V_f. Flax preforms need to possess a significantly higher off-the-loom V_f to compete with the results achieved to date from viscose rayon or laminate control samples. A maximum fibre volume of 50–55% is achievable in the near future using certain fibres. The control over fibre proportions in each orientation is an advantage for 3D woven fabrics to enable higher fibre volume fractions within layers and, in turn, in the whole component. The challenge however, is working within the manufacturing and design constraints to maintain an engineered, specific architecture from design schematic through to composite component.

15. CONCLUSIONS

Dobby and Jacquard technology can produce 3D reinforced angle interlock architectures in flax and viscose yarns with composite volume fractions in the starting range of 20–40% respectively. The use of viscose rayon negates some of the disadvantages of flax fibres such as batch variability, need for alkali or enzyme pre-treatment at a more desirable cost. Finding the optimum fabric architecture and fabrication process suited for viscose rayon preforms is crucial to alleviate levels of yarn distortion experienced within the composites. Flax composites demonstrate a robust yarn that resists deformation but requires a higher density preform to give a more representative comparison against baseline control samples. Poor off-the-loom volume fraction is an area that requires urgent address if performance is to improve.

An epoxy resin system was utilised successfully in the production of VARTM processed viscose rayon and flax composites. Flexural strength and flexural modulus results are encouraging when compared with leading non-woven research with viscose rayon/epoxy composites comparable to 2D woven glass fibre composites. The Alkali treatment of flax yarns and composite preforms resulted in decreased tensile and flexural performance. The damage resistance was found overall to be higher in the 3D Angle Interlock viscose rayon composites compared to the 2D 2/2 twill composite. The through-the-thickness reinforcement prevented damage from propagating throughout the structure thus avoiding the type of mass uniform delamination damage observed in the 2D composite.

These initial findings provide significant motivation to improve the design of 3D weave architectures that respond directly to the findings embodied in this research. Work will continue from the initial baseline data discussed in this paper to provide future natural fibre preforms targeted specifically at improving damage resistance and flexural strength.

Due to the challenging processing and performance characteristics desired in engineering composite applications, there are limited bio-derived resin systems commercially available which achieve the desired viscosity profile and are completely sustainable in origin, but their inevitable development represents significant stages on the route to entirely biodegradable thermoset composites.[24] Introducing a naturally-derived sustainable reinforcement, such as the samples reported in this research, contributes significantly in the quest to achieve a fully sustainable natural fibre reinforced composite.

Acknowledgment: The authors acknowledge the financial support of The Arts and Humanities Research Council (AHRC) in the UK for the project entitled 'The Development of 3D Reinforced Natural Fibre Woven Preforms and Eco-Composites,' University of Ulster Belfast, 2007–2009. The authors also acknowledge the contribution of Mrs. Donna Campbell, (Research Associate) for woven fabric production.

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Received: 18 November 2009. Revised/Accepted: 9 March 2010.

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